4.—Bronzite Peridotite and Associated Metamorphic Rocks at Nunyle, Western Australia

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The field occurrence and petrology of an ultrabasic body is described in detail, and observations on the associated metamorphic country rocks and later intrusives are recorded.

The ultrabasic body consists almost entirely of massive bronzite peridotite which has, however, been completely serpentinized in places. Secondary hornblende occurs throughout the body and is particularly abundant near the margins.

The bronzite peridotite has intruded the gneiss, quartzite and basic granulites of the Jimperding "Series". Although definite transgressive contacts occur in the southern part of the area mapped, the ultrabasic mass is generally conformable with the surrounding country rocks.

The intrusion occurred after the main period of regional folding, and at a metamorphic grade probably equivalent to lower amphibolite facies. It resulted in the distortion of the adjacent quartzite, together with flowage and recrystallization of some of the gneisses and basic granulites. The ultrabasic mass was apparently serpentinized by autometasomatism soon after emplacement; all of the serpentine which had formed at this stage has recrystallized to antigorite. Pegmatite dykes cutting the ultrabasic body have produced talc, anthophyllite and clinochlore by silicification of the bronzite peridotite. The secondary hornblende probably also formed during pegmatization.

Transgressive dolerite has caused minor hydrothermal alteration of the ultrabasic mass and a suite of rodingites has resulted from the metasomatism of bronzite peridotite and serpentine by lime and alumina from the dolerite.

Introduction

The bronzite peridotite mass is about four miles north-east of Toodyay at Nunyle (longitude 116°31′ E, latitude 31°31′ S). Toodyay is 53 miles by road and 65 miles by rail north-east of Perth. The main road from Toodyay to Goomalling passes a quarter of a mile to the south of the area studied (see Figure 1).

The aim of this investigation was to examine the relationship of the bronzite peridotite mass to the surrounding metamorphic rocks, and to study the petrology of the ultrabasic rocks.

An area 3,400 feet from north to south and 2,000 feet from east to west was mapped in detail. All locations cited in the text are referred to the south-west corner of the area. Using a six figure group, in which the first three figures are "tens of feet" east, and the last three figures are "tens of feet" north, any point within the area mapped can be specified to within ten feet. One hundred and thirteen specimens were collected and examined. A detailed account of the petrography of these rocks is available in manuscript form at the Department of Geology of the University of Western Australia. Specimen numbers cited in the text are those of specimens held in the collection of that department.

Previous Geological Investigations

Before the present study, almost all of the geological work in the Toodyay district had been confined to the south-west of the Avon River. The name "Jimperding Series" was proposed by Clarke (1930, p. 167) and a detailed petrological examination of the Jimperding "Series" in the Toodyay district was made by Prider (1944). According to Prider (1944, p. 84): "This series comprises pelitic and psammitic metasediments with intercalated basic and acid igneous bands. A study of the pelitic members shows that over the whole area mapped the rocks lie within the sillimanite zone." Farther south, sections of the "series" have been examined in detail at Lawnswood (McWhae 1948) and Hamersley Siding (Johnstone 1952).

Prider (1941) recognized a conformable sequence of Precambrian metamorphic rocks. These represent a variety of sediments with

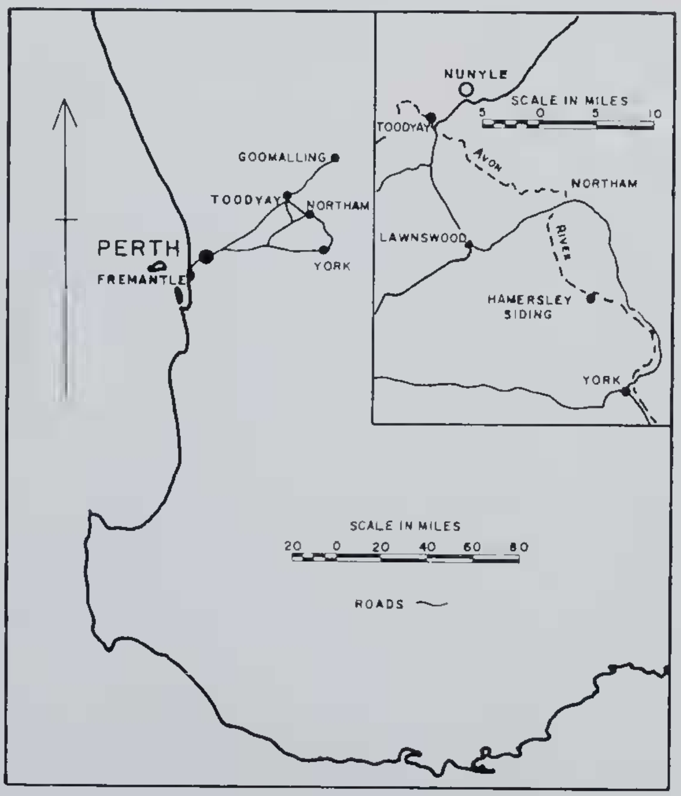

Fig. 1.—Locality map showing south-western Western Australia, Nunyle and the Avon River Valley between Toodyay and York.

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interbedded basic igneous rocks, which may have been sills or flows of tholeiitic character. Two periods of granite emplacement were postulated, with the intrusion of rare ultrabasic dykes both before and after these. Later the rocks were intruded by quartz dolerite.

The rocks at Nunyle, into which the bronzite peridotite was intruded, are a part of the Jimperding "Series". The basic granulites and the quartzite show similarities both in texture and mineralogy to rocks from parts of the "series" which lie to the south-west.

Physiography and General Geology

The Jimperding "Series" which has been briefly described in the introduction, strikes generally north-south at Nunyle, and the rocks have a moderate to steep easterly dip. The country rocks consist of gneiss and quartzite with interbanded basic granulites. The locus of intrusion of the bronzite peridotite is the lower contact of the quartzite and the gneiss and the bronzite peridotite crops out on the immediate west of the quartzite. The contact of the bronzite peridotite and the quartzite is characterised by *Hakea preissii*, which usually grows as rounded bushes about fifteen feet high.

Laterite which is characteristic of much of the surrounding country, does not occur in the area mapped; however, iron stains and quartzite fragments cemented with limonite are common on the higher features and the gneiss and dolerite in the uplands are kaolinized and leached. It appears that these rocks were in the zone of leaching directly below the laterite, which once covered the whole district at about 950 feet above sea level.

Only skeletal soils are developed and these are commonly colluvial containing fragments of quartzite and other rock types, which have come down the hill slopes. Alluvium is common in the valleys, but as solid bronzite peridotite crops out in the creek bed at 020011 (approximately the local base level), it is thought that the alluvium seldom exceeds 10 feet in thickness.

The area lies in the 21" rainfall belt and most of the rain falls between May and August. The Toodyay district is an undulating plateau at about 1,000 feet above sea level, which has been dissected to a maximum depth of about 600 feet by the Avon River drainage system. The area mapped has an elevation of between 680 feet and 970 feet above sea level. Here the streams are young, cascades are common and solid outcrops occur frequently in the creek beds.

The ground water is unusual in that on the hillsides it is saline whereas the springs in the valleys provide excellent drinking water. Many of the creeks in the district are located along fault or shear zones, as evidenced by epidote-filled shears and epidote impregnations in the rocks in the creek beds. These creeks are typically straight and have numerous springs and seepages along their courses. The creeks from 200095 to 180048 and 130012 to 000010 are of this type. The creek from 086279 to 000230 has none of the characteristics outlined above and its course is probably controlled by the quartzite. The river gum (*Eucalyptus rudis*) grows alongside the larger watercourses.

Quartzite crops out strongly forming the most prominent physiographic features in the area. In the creeks on the other hand, exposures of quartzite are rare, indicating that the watercourses tend to pass through any natural gaps in the quartzite rather than to cut down through it. The holly-leafed dryandra, *Dryandra floribunda*, and white gum, *Eucalyptus redunca*, are the typical vegetation on the quartzite hills.

A shear, which has caused local shattering and distortion of the quartzite, has weathered at 100120 to form a remarkable topographic break. Projection along the line of this shear to the south-west shows that it is parallel to the platy flow of the bronzite peridotite outcrops on the immediate north. To the north-east there is no apparent dislocation of the gneiss and the break does not conform with the regional structure. It is related in time and space to the intrusion of the ultrabasic body into a semi-rigid quartzite, and represents distortion of the quartzite during the intrusion of the bronzite peridotite.

Outcrops of gneiss generally occur on the lower hill slopes and in the valleys. Aerial photographs indicate that the gneisses overlying and underlying the ultrabasic body have straight parallel trends, whereas the quartzite (which immediately overlies the ultrabasic body) has a highly variable strike and dip. Examination on the ground shows that there is far more distortion of the rocks in contact with the ultrabasic body than in those a few hundred feet stratigraphically above or below it. The gneiss appears to have flowed into the quartzite and filled openings which occurred during the intrusion of the bronzite peridotite. Shallow valleys at 120300 and 120160 are considered to have resulted from differential weathering of such intrusive gneiss.

York gum, *Eucalyptus loxophleba* and jam, *Acacia acuminata*, are characteristic of the richer soils in the area and generally grow over basic granulites or bronzite peridotite. Where these species grow on quartzite talus, the talus probably overlies basic or ultrabasic rocks.

The bronzite peridotite usually crops out on the hill slopes below the escarpment of the quartzite, in the form of numerous boulders up to about three feet in diameter. In some places, however, the outcrop is in the form of large blocks, which are *in situ*, and are as much as twenty feet in diameter (see Figure 2). Such an outcrop occurs at 048125. The tunnels and crevices under the blocks have been used by small animals, such as foxes, and where these animals have rubbed against the rocks, the surfaces are smooth and polished.

The Ultrabasic Body

Introductory Statement

The ultrabasic body is made up dominantly of bronzite peridotite, with variations from relatively pure serpentinite to pyroxenites which may have little olivine or antigorite.

It is overlain apparently conformably, by quartzite to the east and north, and is underlain by gneisses to the south and west. Definite transgressive contacts have been established between it and the gneisses to the south. Out-

Fig. 2.—The south-western aspect of "Black Rocks", a large outcrop of bronzite peridotite at 048125.

crop in the central and eastern portion of the area is good, but much of the south-western corner is covered by colluvial soils derived from dolerite, quartzite, ultrabasic material and sometimes gneiss. In 1950 a new road was constructed from 000140 to 050230 and the ditch on its south-east side exposes gneisses and quartzite which apparently occur in the centre of the ultrabasic body. The ultrabasic material, in turn, cuts through the gneiss and quartzite in narrow dykes of the order of a few feet wide. Thus the general form of the body appears to be two distinct lenses lying parallel to the strike of the country rocks, connected by a series of narrow dykes.

Planar structures are developed throughout the body; these are considered to be platy flow-structures and mapping has shown that they tend to be parallel to the contacts of the body.

The only mineralogical trend observable in the field is the enrichment in amphibole towards the margin of the body.

No lineations have been recognized in the ultrabasic rocks. The pyroxene may be oriented, but in view of the coarse grain size, it has been impractical to test this. Certain rock slices give pyroxene cross sections with similar orientations, but as most slices only show three, four or at the most twelve cross sections of pyroxene, study by the normal statistical methods is precluded.

Petrography

A bronzite peridotite and a hornblendic bronzitite have been chosen for description as they portray the typical occurrence and interrelations of minerals throughout about 80 per cent. of the intrusive mass. Two serpentinites indicate the character of the remainder of the mass. It has not been possible in mapping to separate bronzite peridotites and serpentinites. Also described are veins having their origin within the ultrabasic body, altered rocks associated with the pegmatite dykes, alteration associated with the quartz dolerite dyke and a small group of rocks thought to be xenoliths.

Bronzite peridotite.—Specimen 39725 was collected from 007032 about two hundred feet from the southern contact of the ultrabasic body with the gneisses. The outcrop consists of numerous boulders mostly *in situ.* In hand-specimen it has a general dark green colour, with pale grey patches (about 10 mm in diameter) making up about 40 per cent. of the rock. It is massive and porphyritic, with hard porphyroblasts in a softer, serpentinous, fine-grained groundmass. Small flakes of chlorite are disseminated throughout the rock.

In thin section the texture is pseudoporphyritic. Large pyroxene porphyroblasts * have inclusions of olivine, some of which are euhedral. No crystal faces are developed on the pyroxene. The following minerals are present: Antigorite (approx. 45%), very fine-grained fibrous or laminated mineral, occurring as pseudomorphs after olivine giving a characteristic mesh texture of "grains" 0.2 mm in diameter. There is a strong tendency for it to be oriented with X and Z lying in the same directions throughout the whole slide. Fine inclusions of magnetite dust occur everywhere within it and particularly along the contacts of "grains" pseudomorphous after olivine. Alteration is to clinochlore by reaction with spinel. *Bronzite* (approx. 33%), rather irregular grains, from 1 to 5 mm in diameter, with abundant inclusions of anhedral, sieve-textured olivine averaging 0.5 mm in

* The term porphyroblast is used here to describe prominent crystals which have grown in a solid or crystalline medium.

diameter, and also of rounded grains of spinel and magnetite 0.1 mm in diameter. *Olivine* (approx. 16%), occurs mainly as sieve-textured inclusions in bronzite 0.5 mm in diameter, and as relics 0.1 mm in diameter in mesh-textured antigorite marginal to bronzite. Some of the grains included in the bronzite show development of the 010, 001 and 021 faces, but such euhedral grains, though significant, are exceptional. Alteration is to antigorite and magnetite dust, or to hornblende. *Hornblende* (approx. 3%), rare prisms up to 0.5 mm long or pseudomorphs after olivine. *Spinel* (approx. 2%), dark yellowish green 5 GY 5/4† rounded grains (0.1 mm in diameter), included in bronzite. Alteration is to magnetite and isotropic, fine-grained chlorite, by reaction with antigorite. No spinel remains except where it is armoured with another mineral against antigorite; reaction rims are not well developed in this specimen. *Clinochlore* (trace), books up to 0.05 mm by 0.3 mm associated with magnetite. These associated laminae cut across the mesh texture and exert their form strongly.

The relationship of the olivine and bronzite in this specimen is most significant. The textures that may be produced from bronzite with abundant poikilitically included olivine will be discussed later.

Hornblendic bronzitite.—Specimen 39739 was collected from 084268 where the outcrop consists of scattered boulders. The rock appears to consist of normal bronzite peridotite (with the typical rough weathered surface) in which are ellipsoidal blebs of material about 9 in. by 4 in. by 6 in. which weather to a smooth surface. These blebs are outlined by a weathered groove, about ½ in. deep and in hand specimen they are uniform grey and of even hardness. Numerous grains of amphibole averaging about 1 mm long compose about 50% of the blebs.

In thin section the texture is poikilitic. Large masses of bronzite enclose numerous hornblende prisms, which in quantity exceed the host crystal. *Bronzite* (approx. 40%), forms oikocrysts up to 5 mm in diameter, which are cut by small veins of antigorite and chrysotile. Alteration is to chrysotile. *Olivine* (trace), occurs only as rare relics in mesh-textured antigorite intergranular with respect to bronzite. *Hornblende* (approx. 52%), occurs as euhedral, subhedral or anhedral prisms included in bronzite and is commonly traversed by chrysotile veins.

This specimen is notable in several respects:—

(a) The absence of spinel and clinochlore both of which are found almost universally throughout the ultrabasic body. Possibly both of these minerals were in the rock, but they have now been altered and their components used to form hornblende. (b) The absence of olivine included in the bronzite. Conditions appear to have been particularly favourable for the formation of hornblende, and included olivine would have been converted to hornblende. (c) The predominance of hornblende inclusions and the general texture. There is a textural similarity in thin-section between this rock and specimen 39725, in which the bronzite porphyroblasts have abundant inclusions of sieve-textured and euhedral olivine.

Serpentinite.—Specimen 39751 was collected from 040120, which is 50 feet south-east of Black Rocks. The outcrop consists of scattered boulders, with smooth weathered surfaces. In hand specimen the rock is greyish green, uniformly soft and has an uneven fracture.

In thin section the specimen has a fine-grained feathery texture with some recognizable mesh-texture Areas up to 3 mm across contain reticulate, or knitted-textured masses of antigorite. *Antigorite* (approx. 90%), occurs as feathery groundmass, in reticulate areas, and as anhedral "grains" up to 0.8 mm in diameter. Much is recrystallized and oriented so that when the nicols are crossed and the gypsum plate inserted, if the stage is rotated the field appears alternately dominantly orange and blue. *Magnetite* (approx. 3%), is present as fine inclusions up to 0.2 mm in antigorite, and as ragged grains up to 1 mm in diameter associated with chlorite. *Chlorite* occurs as laminae frequently associated with magnetite grains or laminae. The characteristic occurrence is in books 0.3 mm by 0.1 mm. Two varieties were recognized, *clinochlore* (approx. 3%) and *pennine* (approx. 4%). The variation between these two varieties is probably continuous. Clinochlore formed by the reaction of antigorite with aluminous spinel, and positive and negative pennine resulted from a reaction between relatively aluminous clinochlore and antigorite.

This rock is a highly serpentinized bronzite peridotite in which the original pseudoporphyritic texture is preserved. The reticulate masses of antigorite, 3 mm in diameter, represent earlier porphyroblasts of bronzite.

Serpentinite.—Specimen 39734 was collected at 048129, that is, on the immediate north of Black Rocks from an outcrop of scattered boulders. The hand specimen is a uniform, fine-grained dark green rock with numerous minute silvery chlorite flakes. Under the microscope the rock appears to consist dominantly of antigorite with the characteristic mesh texture, in which are several partly serpentinized hornblende prisms and also a bronzite porphyroblast altered to structureless serpentine. The chlorite flakes are always associated with magnetite laminae. This rock bears a striking resemblance to specimen 15425 (collected from a dyke just south of Toodyay) described by Prider (1944, p. 128) which was shown from analysis to be a normal serpentinite.

Veins having their origin within the ultrabasic body.—A variety of veins have their origin within the ultrabasic rocks themselves. They are easily distinguished in hand specimen as they are normally subject to differential weathering with respect to the enclosing rocks. In thin section however, they have less distinct boundaries, being composed of altered or recrystallized minerals on a planar or distorted planar surface. The chrysotile veins are of particular interest for it is veins of this character which

† Colours of minerals given are from the colour standards of the Rock-Colour Chart prepared by the National Research Council, Washington, D.C

Fig. 3.—Polished specimen (x ½) showing bronzite crystals (pale grey) in a serpentinous groundmass (dark grey). The left half of the specimen consists of normal bronzite peridotite, in the centre-right is the pyroxene-rich vein, to the right of this is the zone of intense serpentinization, and on the extreme right there is normal bronzite peridotite. A magnetite-clinochlore vein passes from the upper left of the specimen to the lower right of the pyroxene-rich vein, but does not stand out strongly in the photograph.

form the commercial deposits of chrysotile asbestos elsewhere. Further, chrysotile veins alone have produced noticeable dilation.

Pyroxene vein.—The only outcrop of this type of vein may be seen on the northern vertical surface of the outcrop referred to as Black Rocks. The vein has a relief of about 1″, is about 2″ wide and crops out for a length of some 30 feet. Specimen 39727 is 13″ by 9″ by 6″, and one face of it has been polished to reveal the relationship of the vein to the enclosing bronzite peridotite (see Figure 3). The rock and the pyroxene vein are both traversed by magnetite-clinochlore veins.

Inter-relations of the minerals in the vein are essentially the same as in the normal bronzite peridotite. Large bronzite porphyroblasts comprise about 66% of the vein; olivine included in the pyroxene and adjacent to the pyroxene has been partly preserved from serpentinization. On one side there is a zone of intense serpentinization. The only feature fundamentally distinguishing the vein from the enclosing rocks is the high proportion of bronzite.

Magnetite-clinochlore veins.—These are present in specimen 39727 and are relatively abundant throughout the rest of the ultrabasic body. As seen in thin section they consist of strings of roughly equidimensional composite grains (averaging 0.2 mm in diameter), which are composed of alternating lamellae of clinochlore and magnetite. They may transgress bronzite crystals in which case the bronzite immediately adjacent to the vein is altered to clinochlore.

Magnetite-antigorite veins.—These veins are characteristically weathered to a depth of up to 4 mm deeper than the surrounding rocks, giving an entrenched appearance. Under the microscope they appear as numerous strings and groups of magnetite granules and occasional composite magnetite-clinochlore grains in a serpentinous material. Examination under high power magnification shows that some of the magnetite consists of dust (0.001 mm in diameter) surrounding antigorite "grains", which are approximately 0.02 mm in diameter. The antigorite is oriented with X normal to the plane of the vein. The veins themselves are traversed by gamma chrysotile veins.

Bronzite peridotite breccia.—Specimen 39754 was collected at 057290. The zone of brecciation is not more than a few feet wide, and in it the bronzite peridotite is broken into angular fragments averaging 40 cm in diameter. The groundmass is composed of antigorite and magnetite with numerous fine striae parallel to the margins of the fragments. The antigorite is either in large crystals or else in parallel-oriented small crystals since areas up to 4 mm in diameter show essentially the same optical orientation. This brecciation appears to be a late-stage effect due to adjustments within the ultrabasic mass after its consolidation.

Chrysotile veins.—These are typical cross-fibre chrysotile veins and occur in two varieties. The oldest is characteristic of the more highly serpentinized rocks and forms swarms of intricately distorted thin lenses averaging 0.02 mm in thickness. This variety appears to be more recent than any antigorite-bearing veins or antigorite in the groundmass of the bronzite peridotite. These irregular thin veins are in turn cut by young regular chrysotile veins which are of uniform sheet-like form from 0.1 mm to 1.0 mm in thickness. These later veins exhibit only minor distortion.

Fig. 4.—Zoned chrysotile vein cutting serpentinite. Crossed nicols, x 15.

Altered rocks associated with the pegmatite dykes.—The ultrabasic mass has been intruded by several small pegmatite dykes and addition of material has caused considerable local alteration.

At 110010 on the south bank of the creek, some tens of feet from a pegmatite dyke, bronzite has been altered and replaced by a fine-grained felted mass of hornblende (25%), clinochlore (30%), talc (35%), anthophyllite (10%) and magnetite (trace). The original groundmass, presumably antigorite, has been mainly replaced by hornblende, which is medium-grained and comprises about 90% of the present groundmass. Thus the pseudoporphyritic texture is preserved even though the mineralogy has been almost entirely changed.

Xenoliths of ultrabasic material included in the pegmatite dykes have been very extensively altered, and all former textures destroyed. The amphiboles, however, are still those of the ultrabasic body. A typical xenolith is 8 in. in diameter and has a core composed entirely of pure coarse-grained hornblende; clinochlore, magnetite, spinel and the serpentine minerals are conspicuous by their absence. Surrounding this core is a rock in which hornblende is still dominant but chlorite, vermiculite or chlorite-vermiculite mixtures comprise about 30% of the rock. Talc or anthophyllite may be present. The outer shell of the xenolith is either chlorite or vermiculite schist one or two inches thick and is very friable. In one specimen examined alteration had proceeded to a stage at which hornblende had been corroded and replaced by oligoclase. The resulting rock is composed 60% of hornblende, 30% of oligoclase (An_{13} — An_{37}), and 1% of quartz.

Talc bodies are found in the vicinity of the pegmatite dykes. These have a core of talc of variable thickness and are separated from the bronzite peridotite by a sheath of anthophyllite needles of the order of 4 cm long, oriented with their *c* axes normal to the contact. Anthophyllite may also occur in the core as feathery masses but is always heavily corroded by talc, which is either pseudomorphous after anthophyllite or in irregular masses. Interleaved with the anthophyllite needles are rare flakes of vermiculite and pennine (cf. specimen 39765).

One of the talc bodies had a core consisting of about 80% of talc with corroded inclusions of chlorite (diabantite) up to 1 mm in diameter, anthophyllite and hornblende being present in trace quantities.

Anthophyllite and talc are the products of progressive silicification; chlorite has resulted from alteration in an environment rich in water but deficient in silica, but subsequent addition of silica has led to steatitization of the chlorite.

Alteration associated with the quartz dolerite dyke.—A quartz dolerite dyke about 150 feet wide has been intruded across the south-western part of the area studied. Near this dyke bronzite has been extensively altered to talc, hornblende and anthophyllite. This alteration started along cracks and cleavages and worked outwards converting adjacent bronzite to amphibole. Antigorite is present in the normal quantities but occurs as a feathery groundmass with associated pennine and magnetite. Distinct mesh texture is not developed.

At 036014 the bronzite peridotite has been completely altered to a very fine-grained mass of intricately intergrown clinochlore and talc. No amphiboles are present at this locality.

Xenoliths in the ultrabasic body.—In certain areas there are patches of mixed float of bronzite peridotite and amphibole schist. These amphibole schists are thought to be xenoliths, as their general appearance is different from either the country rocks or the ultrabasic rocks. Three specimens which are essentially quartz-tremolite schists have been examined in detail. The texture varies from schistose to granoblastic with poor platy orientation and there may be a poor or a strong linear orientation. The colour is pale green but may be reddish due to oxidation. Tremolite (9%-100%) occurs as subhedral prisms with lamellar twinning parallel to 001. γ = 1.630 — 1.648, apatite and monazite are common inclusions, alteration is to talc. *Quartz* (trace — 90%) forms equant to elongate grains with inclusions of apatite, monazite and more rarely rutile.

The tremolite is similar to the amphiboles of the ultrabasic body and quite unlike the hornblendes of the basic granulites in the country rocks. As all the outcrop is in the form of float it has not been possible to correlate the lineations with any structure elsewhere. These rocks have a mineralogical affinity with the ultrabasic rocks but have different textures, the accessory minerals apatite, monazite and rutile, and occur only within the boundaries of the ultrabasic body.

Mineralogy

Olivine varies from forsterite to chrysolite. Originally this mineral probably constituted over 95% of the "magma", but now, due to silicification and serpentinization, it is uncommon to find rocks with more than 5% of olivine. β ranges from 1.663 to 1.674 indicating a variation in composition from Fa.7 to Fa.12 (Poldervaart 1950). Spinel is a rare inclusion. Where the inter-relations can be seen, olivine is idiomorphic towards pyroxene, though it is usually embayed until only sieve-textured relics remain. Bronzite, hornblende and chrysotile have evidently all formed from olivine under appropriate conditions, but usually chrysotile appears to have recrystallized to antigorite.

The only *pyroxene* encountered is bronzite. No 010 sections of clino-pyroxene have been seen, nor have any sections perpendicular to the optic axes given figures similar to those of clinoyproxene. Nevertheless clinopyroxene present in small amounts would be difficult to detect unless the grains were favourably oriented.

Bronzite occurs throughout the ultrabasic body except where it has been serpentinized or metasomatized to produce hornblende or talc and anthophyllite. Even where complete serpentinization has occurred, structureless serpentine pseudomorphs, or knitted-texture antigorite pseudomorphs testify to the earlier presence of pyroxene. Similarly where the rock has been metasomatized, talc, or talc-anthophyllite pseudomorphs after pyroxene clearly indicate its original presence. These pseudomorphs are equivalent in size to the fresh pyroxenes and are also present in the same proportions with respect to the groundmass, as the pyroxenes are in the less altered rocks. Measurement of 2V and γ has shown that these pyroxenes are aluminous (see Table I) and do not conform with the composition—optical property diagram of Poldervaart (1950). As the percentage of ferrosilite is between 11 and 25, and the Mg:Fe ratio is between 9 and 2.33, all these pyroxenes are bronzite. This nomenclature is in accordance with Poldervaart (1950) even though some of these pyroxenes contain less than 70% of enstatite.

In thick sections the bronzite is pleochroic with X colourless, Y pale pink and Z pale green.

The bronzite porphyroblasts are distinctive not only in thin-section and hand specimen but also in their persistence in shape and size in replaced and altered parts of the ultrabasic body. Their origin and relation to other minerals is of interest. There are three important points in the inter-relations of olivine and bronzite. First, the bronzite is never euhedral and never shows any crystal faces; second, the bronzite usually includes sieve-textured or embayed olivine which was probably once euhedral (cf. specimen 39725); third, the margins of the bronzite porphyroblasts are commonly rich in olivine inclusions, in fact some may be so well coated with olivine that the serpentinous groundmass of the rock is only rarely in contact with the pyroxene. The bronzite porphyroblasts are the result of introduction of silica into an aggregate of olivine crystals. Thus, the porphyroblasts contain relic granules of olivine cemented together by bronzite formed by the silicification process; the persistence of olivine depended upon the availability of silica and the armouring effect of the already-formed bronzite.

Spinel is found in all of the less-altered bronzite peridotites. Grains of ragged magnetite associated with clinochlore in the serpentinites testify to the earlier presence of spinel. The stages—spinel, spinel with magnetite and fine-grained chlorite reaction rims, spinel with magnetite-clinochlore reaction rims, and finally magnetite grains with clinochlore—clearly illustrate the progressive "serpentinization" of these grains. The normal amphibole, a near-tremolite, is apparently undersaturated with respect to Al_2O_3. Regional metamorphism has led to the absorption of magnetite and spinel by hornblende. Although the previous existence of spinel in these rocks cannot be proved, it was clearly present in the rest of the ultrabasic body to the extent of 1 or 2 per cent.

TABLE I

Estimation of the composition of pyroxenes (from the optical data diagram of Winchell and Winchell 1951, p. 406).

Specimen	2Vz	γ	Enstatite	Ferrosilite	$Al_2Al_2O_6$: $HAlSi_2O_6$
39725	78°	1·670	79%	11%	10%
39726	87°	1·675	68%	14%	18%
39728	81°	1·676	70%	11%	19%
39729	78°	1·676	73%	11%	16%
39735	84°	1·670	71%	14%	15%
39736	84°	1·676	71%	14%	15%
39737	88°	1·669	70%	16%	14%
39738	83°	1·673	71%	13%	16%
39749	90°	1·671	69%	16%	15%
39750	107°	1·678	60%	25%	15%

The refractive index varies from 1.778 to 1.786. As the grains are generally less than 0.2 mm in diameter, no measurements of specific gravity have been attempted. The variety is probably ceylonite or pleonaste. The colour is close to moderate yellowish green 10 GY 4/4, with variation in hue and absorption towards light olive 10 Y 5/4.

Regional metamorphism has caused the partial recrystallization of the ultrabasic rocks to produce *hornblende*. There is no primary hornblende. Near the contacts with the country rocks it is abundant, but towards the centre of the mass it is rarer, being of the order of 10% or less. Hornblendites are developed adjacent to the pegmatite at 109010.

The optical properties of the hornblende vary over a well-defined range, viz:—γ 1.640-1.655 (mean 1.645); 2Vx 75°-90° (mean 85°); Z $\wedge$ c 17°-21° (mean 18°); β 0.017-0.022 (mean 0.019). These properties vary independently and so no generalizations can be made regarding the trends or changes in the composition of the hornblende. The composition is evidently near to tremolite with Mg:Fe = 85:15. In hand specimen the hornblende is dark green, but in thin section it is almost colourless, except in some rocks rich in hornblende. The strongest colours recorded were X very pale yellowish green (10 GY 8/2), Y pale yellow-green (10 GY 7/2) and Z pale green (5 G 7/2) with absorption $X < Y$ Z. In the centre of the body hornblende has formed from olivine and pyroxene, but near the margins and adjacent to pegmatite, the serpentinous groundmass has sometimes recrystallized to give hornblende. Where hornblende occurs as an alteration product of olivine, both included in bronzite and in mesh-textured antigorite, this has produced interesting results in the mesh texture; cores of olivine may be seen surrounded by successive rims of antigorite, hornblende and antigorite. The sequence was evidently partial serpentinization of olivine, then alteration of the outer part of the remaining olivine to hornblende, followed by renewed serpentinization of the olivine.

Three distinct *serpentine minerals* are recognized, α and γ chrysotile and antigorite. *Alpha chrysotile* is characterized by negative elongation (Tertsch 1921, p. 188) and $\beta \leq 1.560$ (Nagy and Faust 1956, p. 821). It occurs in fresh mesh texture particularly where there are olivine relics. *Gamma chrysotile* has positive elongation, $\beta \leq 1.560$ and is found in fresh mesh textures and also in late veins.

Antigorite is present in four textural forms, the most interesting of which is the "oriented mesh texture". Initially mesh texture was characterized by each "grain" containing radially oriented chrysotile. When seen under crossed nicols, insertion of the gypsum plate gives the field evenly balanced blue and orange interference colours in adjacent quadrants. Recrystallization of the chrysotile to antigorite did not destroy the meshes but the previously radial arrangement was replaced by a parallel orientation. With the recrystallized antigorite, insertion of the gypsum plate then gives the field alternately blue and orange interference colours on rotation. The orientation may be dominantly parallel throughout the whole of a thin section. The relationship of this orientation to the regional tectonic axes has not been determined, for it is not known yet whether the orientation is parallel locally, or parallel throughout the whole of the ultrabasic body. This recrystallization may be related to the regional metamorphism, as the regional metamorphism would affect the temperature and the availability of the ions Al^{+++} and Fe^{+++}. Suggested processes for the development of antigorite from chrysotile were outlined by Nagy (1953), and Wilkinson (1953, p. 315) noted that in the alpine-type serpentinites of Queensland, chrysotile has recrystallized to antigorite at a grade equivalent to the albite-epidote facies.

Antigorite also occurs in patches of similar dimensions to the pyroxene porphyroblasts. These patches either have knitted-texture, which is similar to mesh texture, with the exception that the meshes are of the order of 0.02 mm in diameter, or else take the form of anhedral structureless pseudomorphs after pyroxene. In both cases the texture of the original rock is usually preserved. Another mode of occurrence is in veins, in which the antigorite lamellae are disposed at right angles to the plane of the vein. Strings of magnetite grains are frequently arranged parallel to and within these veins. Antigorite with this texture is also found irregularly distributed separating patches of undisturbed mesh texture. Recrystallization of chrysotile or antigorite with minor contemporaneous movement, which has partially destroyed the original mesh texture, would give rise to such antigorite-magnetite veins. The refractive index β = 1.566-1.572 (mean 1.568). The birefringence was estimated to be consistently about 0.003, which is rather low for antigorite.

Magnetite is found in all the ultrabasic rocks except the hornblendites. It is nearly always a product of serpentinization either of olivine or bronzite, or of the reaction of a serpentine mineral with spinel. Magnetite does not occur in hornblendites and is normally corroded in rocks rich in hornblende. Inclusions in pyroxene may be primary magnetite, but these are rare and will not be considered further. The common association of chlorite with magnetite is interesting for two reasons. First, the associated minerals may have been formed by the break-down of one previous mineral containing the sesquioxides Fe_2O_3 and Al_2O_3 and second, the chlorite only rarely contains more than 15% of ferro-antigorite or daphnite.

Chlorite appears to be derived entirely from the reaction of aluminous minerals with serpentine, or as a result of the introduction of alumina along veins into serpentinites. It is common to all rocks containing serpentine and most of those affected by hydrothermal activity.

The refractive index β varies between 1.590 and 1.573; the birefringence is usually 0.006, with buff polarization colours, but varies to give very low order anomalous blues; 2V is variable being up to about $+30°$ in some clinochlore. Thus, the common chlorite is aluminous, i.e. clinochlore. Silicification associated with either talc or antigorite has led to the formation of diabantite in specimen 39765 and probably penninite in specimen 39751 (Hey 1954, pp. 280-284).

The development of clinochlore from serpentine and spinel has been discussed previously; the association of magnetite and clinochlore laminae is described here. The associated laminae occur both as discrete "grains" scattered through the rock and also in well-defined veins such as those in specimen 39727. The alumina necessary to produce clinochlore was probably introduced along fissures, where it reacted with the serpentine to produce clinochlore plus magnetite. The laminated form of the magnetite could be due to either the crystalloblastic forces of the chlorite which expelled iron ore parallel with the 001 face, or, the formation of a chlorite supersaturated with iron, which was later deposited by exsolution in laminae parallel to 001. The clinochlore may have reacted later with antigorite and given rise to the negative penninite (low alumina), which is commonly interleaved with clinochlore. A similar transition from optically positive to optically negative chlorite has been noted by Francis (1956, p. 213). The associated laminae are always idioblastic towards, and appear to be later than antigorite.

Chlorite was also formed by the hydrothermal alteration of pyroxene and probably olivine, which produced books frequently up to 2 cm in diameter with very little magnetite. Continued hydrothermal activity sometimes led to the formation of talc. Alteration to talc involved addition of silica and proceeded from embayments, to sieve-textured inclusions of chlorite in talc, and ultimately probably to pure talc. During this process the character of the chlorite itself changed from the early aluminous clinochlore to the more siliceous diabantite.

Alteration of chlorite also gave rise to *vermiculite* locally. At 109010 there is a talc-vermiculite-hornblende schist, and at 107010 an equivalent rock consists of clinochlore and hornblende. Over a space of about twenty feet, on one side the chlorite has all been altered to vermiculite, while on the other side there are only traces of alteration. Specimen 39765 shows apparent equilibrium between talc and vermiculite, both of which appear to have formed at the expense of chlorite. Some vermiculite is idioblastic towards talc, but much of it is evidently replaced, heavily embayed, chlorite.

The stage at which vermiculite formed is obscure. The evidence in specimen 39765 could indicate that some chlorite was being steatitized and simultaneously other chlorite was being converted to vermiculite, which was incapable of being steatitized. Further, there is the difficulty presented by almost adjacent rocks having fresh chlorite or vermiculite. The problems associated with vermiculite have been investigated by Barshad (1948), who concluded that they were essentially micas with the K replaced by Mg or Ca. He recognized four types; vermiculite as described above; vermiculite-biotite mixtures; vermiculite-chlorite mixtures; and biotite-chlorite mixtures. By utilizing the base exchange capacity he could convert three of these types to biotites. The vermiculite-chlorite mixtures, however, while otherwise similar were not so in this respect (Barshad 1948, pp. 675-677). It is probable that the vermiculites described here are vermiculite-chlorite mixtures, as they are obviously derived from chlorites. The flakes do not exfoliate appreciably when heated.

The common occurrence of vermiculite near two pegmatites indicates that hydrothermal action was involved in its genesis. Alternatively, the hydrothermal action gave rise to chlorite which, on weathering, was converted to vermiculite.

Talc and *anthophyllite* are hydrothermal alteration products of the ultrabasic rocks. Anthophyllite never appears to be in equilibrium with the surrounding minerals, but seems to be an intermediate product between the unaltered rock and talc. This accords with the findings of Bowen and Tuttle (1949, pp. 450-452), and Yoder (1952, pp. 609-614) who considered that the stability field of anthophyllite existed in a water-deficient region (a condition which would be unlikely to obtain adjacent to a pegmatite during steatitization).

These minerals generally occur together, often with clinochlore. Hydrous emanations from the dolerite have resulted in very irregular masses of inter-mixed talc and anthophyllite, which may be roughly pseudomorphous after bronzite. The pegmatites are responsible for larger masses of talc sheathed in fine needles of anthophyllite. In such anthophyllite 'γ' varies between 1.625 and 1.631, indicating approximately 95% of magnesian anthophyllite (Rabbitt 1948, p. 295).

It is interesting to note that serpentinization of amphiboles has not been found in rocks containing significant proportions of talc.

Talc is the most silicified magnesian silicate found, being the last member of series which might be written:—

forsterite—enstatite—anthophyllite—talc

At Nunyle, talc appears to be the only member of that series capable of coexisting with quartz and its association with anthophyllite is an expression of silica deficiency in the rocks.

*Rock Facies**

Three equilibrium mineral assemblages can be recognized; these are:

Olivine, Bronzite, Spinel	= Bronzite peridotite
Hornblende	= Hornblendite
Antigorite, Magnetite, Chlorite	= Serpentinite

* The word facies is used here to express an environment in which the most important variables are temperature and composition.

The percentage of minerals belonging to each assemblage for every specimen examined (specimens with abundant talc and anthophyllite have been excluded), has been computed and the results plotted (Figure 5). Thus two hornblendites and seven serpentinites are the only rocks containing minerals all of which belong to a single assemblage. The remaining points represent specimens containing mixtures of the three assemblages.

A quick examination of Figure 5 shows that rocks are likely to occur with mixtures of the three assemblages in all proportions. The majority of the rocks, however, have a ratio approaching hornblendite: bronzite peridotite = 1 : 4. The subdivisions within the triangle divide the rocks into those described as bronzite peridotites, serpentinites and hornblendic bronzite peridotites respectively.

The minerals of the bronzite peridotite assemblage evidently represent the facies which obtained during the intrusion. All the minerals are more or less altered so that no bronzite peridotites remain, which do not show the effects of serpentinization, regional metamorphism, or more commonly, both. This assemblage is important for it is the parent of both the hornblendites and the serpentinites.

The hornblendites probably represent the metamorphic facies of regional metamorphism. All other minerals appear to have been absorbed into the hornblende, which has a composition near to tremolite. The effects of regional metamorphism are naturally very noticeable near the contacts with the country rocks, for in the centre of the ultrabasic mass hornblende comprises less than 10 per cent. of the rock, whereas within one hundred feet of the margins hornblende commonly makes up more than 40 per cent. of the rock.

The serpentinites could have represented the green schist metamorphic facies of Turner and Verhoogen (1951, p. 472). Chrysotile was unstable under the regional metamorphism, but chrysotile and magnetite must have been stable minerals during serpentinization. There are

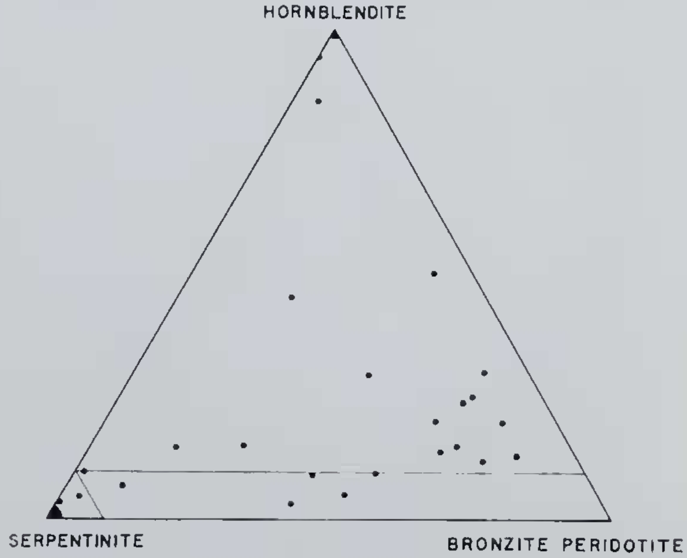

Fig. 5.—"Rock Facies" diagram.

certain reactions between chlorites and talc within this assemblage, but these are only adjustments of chemical compositions and not changes of mineral types.

All these assemblages are of the same parentage and the minerals of all of them may be found today, often within a single specimen. Therefore, while pressure and temperature conditions might have favoured various assemblages from time to time, only in certain localities were the reactions completed, and the equilibrium assemblages attained. To explain the reason for this failure, let each facies be represented by the characteristic mineral, say enstatite, tremolite, and antigorite. The formulae of these, calculated to constant MgO, are: —

$15MgO$	$15SiO_2$	(enstatite)
$15MgO$	$24SiO_2$ $3H_2O$ $6CaO$	(tremolite)
$15MgO$	$10SiO_2$ $10H_2O$	(antigorite)

From this it is apparent that there can be no change of assemblage without the requisite chemical conditions. Also, a rock of one bulk composition is not represented in another facies by a rock of the same bulk composition.

Lime, silica and water must have been available for the formation of hornblendites; similarly water was required for serpentinization. The details of these reactions are not understood, but the general trends are clear. Mention has been made above of the probability of regional metamorphism being responsible for the recrystallization of chrysotile to antigorite. If so, then the absence of lime has inhibited the formation of hornblende.

The relationship of serpentinization to regional metamorphism is shown by the interrelations of antigorite and hornblende. In some localities hornblende is partly serpentinized, while elsewhere it appears to have grown at the expense of antigorite. Thus, there is a confusing picture of penecontemporaneous serpentinization and regional metamorphism.

If the bronzite peridotite was intruded during regional metamorphism, abundant water included in the "magma" would cause serpentinization at temperatures below 500°C (Bowen and Tuttle 1949, p. 453). Introduction of lime at the margins could cause crystallization of tremolite, while at the same time excess silica from pegmatites would produce anthophyllite and talc bodies. All these reactions could run at temperatures of the order of 400°C to 500°C and changes of pressure would have had little effect on the mineral assemblages (Yoder 1952, p. 618). The remaining variable, the chemical environment, has been the most significant factor in determining the rock facies.

The existence of a partly open system, in which dominant water produced serpentinites and the presence of lime produced hornblendites, has been demonstrated. At the same time the degree of permeability of the system is expressed by the abundance of hornblende near the margins and its comparative rarity in some of the central parts of the body.

Serpentinization

Although the problem of serpentinization has not been studied in detail, the following observations are relevant.

The origin of the serpentinizing fluids is controversial, and in current literature there are three general theories. First, the fluids formed part of the magma; second, they were derived from adjacent rocks (i.e. connate water from sediments, or hydrous emanations from granites); third, they were of supergene origin. At Nunyle, the country rocks were already partly metamorphosed at the time of the intrusion, and were gneisses and pyroxene-bearing granulites. If the main period of metamorphism was after the intrusion, it is difficult to imagine how some of the country rocks were "upgraded" to hypersthene-bearing granulites, while only small amounts of tremolite were produced in the ultrabasic body. It is therefore considered that the bronzite peridotite was intruded into relatively anhydrous gneisses and pyroxene-bearing granulites, which could not have contained the water necessary for serpentinization.

Serpentinization must have occurred at considerable depth, as it preceded at least part of the regional metamorphism, thus eliminating the possibility of supergene serpentinization. The country rocks could not have contributed sufficient water so the remaining possibility is that the fluids formed part of the "magma". Notwithstanding the work of Bowen and Tuttle (1949, pp. 439-460), the existence of a magma, which had the composition of the primary peridotite magma of Hess (1938) is indicated by field observations at Nunyle.

Hydrothermal Activity and Late Veins

The ultrabasic body has been considered in terms of three distinct rock facies, each of which is defined by a group of minerals. In this section the veins and minor activities within the body are considered.

The earliest vein found is the pyroxene-rich vein (cf. specimen 39727), in which occurs the last crystallization of anhydrous magnesian silicates. This vein is considered to have formed after the intrusion but before serpentinization, as the vein is not dislocated by the intrusion, and there is no relic antigorite included in the pyroxene. A suggested origin for veins of this type is given by Bowen and Tuttle (1949, p. 460). Water vapour saturated with SiO_2 moving through a fissure in dunite would convert the wall rocks to pyroxenite, producing, in effect, a dyke of pyroxenite cutting dunite.

The ultrabasic rocks were then serpentinized and metamorphosed. During the later stages of metamorphism they were intruded by pegmatites which gave rise to the minerals anthophyllite, talc and chlorite. The main chemical effect of the pegmatites was the addition of silica probably with minor quantities of alumina.

The pegmatites are clearly post-serpentinization. Magnetite grains, which must have originated during serpentinization, have been corroded by amphiboles which crystallized during the pegmatite intrusion. Later serpentinization was probably on a very reduced scale.

Antigorite and magnetite-clinochlore veins appear to have been approximately contemporaneous. They are probably the result of late adjustments of the solidified intrusion as is indicated by the brecciated bronzite peridotite and the small displacements along magnetite-clinochlore veins. Regional metamorphism must have continued during the formation of these veins, though they are later than the main period of hornblende formation, and included amphibole usually shows some serpentinization.

Chrysotile veins are the youngest structures observed in the rocks, which accords with the observations of Wilkinson (1953, p. 309). They consist of cross-fibre chrysotile and are therefore more recent than the regional metamorphism. The majority of the narrower veins are uniform, but the wider ones may show variation in birefringence in zones parallel to the vein.

Anthophyllite-chlorite and anthophyllite-talc-chlorite veins are found in several localities. In each case there is a close field relationship with a dolerite dyke, and at 019240 the minerals talc and clinochlore occur in joints abutting an inch-thick dolerite. Since these veins are generally extremely thin and may be some distance from their parent dolerite, it is considered that the formation of anthophyllite, talc and chlorite must have occurred at relatively low temperatures. The minerals in the veins described here are characteristically anhedral and form only partial replacements of bronzite peridotite, whereas pegmatite activity generally altered the mineralogy extensively.

Calcium metasomatism related to the dolerite intrusion has converted some of the ultrabasic rocks to rodingites. This will be described below under the heading: The Rodingite Suite. No magnesite or chalcedony has been found in the area mapped.

Evolution of the Ultrabasic Body

The history of the ultrabasic body is outlined in Table II. Certain age relations could not be determined; for instance the chrysotile veins are clearly later than the regional metamorphism but their inter-relations with the dolerite have not been observed. Similarly a number of substages in regional metamorphism cannot be placed with certainty in chronological order. Chrysotile could not persist during regional metamorphism, and thus the end of regional metamorphism is placed at the last appearance of antigorite.

The Rodingite Suite

Petrography

Along the western edge of the ultrabasic mass, rocks are found composed of the minerals garnet, prehnite, clinozoisite, diopside and chlorite, which are the characteristic minerals of "rodingites". They are essentially lime-rich ultrabasic rocks and have the outstanding characteristic of light colour and relatively high specific gravity (*c.* 3.0-3.5). None of these rocks have been found in place or in solid outcrop and in two cases specimens were collected from stone heaps which had been made by farmers to facilitate cultivation. Therefore the locations given for specimens serve only to indicate their general positions. The apparent field distribution is along the contact of the ultrabasic mass with the gneisses; however, as the ground slopes upwards to the dolerite dyke only about 100 feet to the east rodingite boulders could have moved to their present positions from the

TABLE II

Time sequence in the ultrabasic body

Stage	Product	Evidence of Relative Age
1. "Magma" genesis	dunitic "magma"	
2. Silicification of "magma"	bronzite porphyroblasts	Olivine is idiomorphic towards bronzite; platy orientation of bronzite shows it is pre-intrusion
3. Intrusion	lenticular mass of bronzite peridotite	transgressive contacts with country rocks
4. Further silicification of intrusion	pyroxene-rich veins	pyroxene vein would have been dislocated during intrusion, hence it is post intrusion
5. Serpentinization and regional metamorphism	mesh-textured chrysotile, and magnetite	initial serpentinization process
(Thermal metamorphism)	mesh-textured antigorite	probably contemporaneous with hornblende formation
(Hornblendization)	hornblendic bronzite peridotite	
(Pegmatite intrusion)	talc anthophyllite and chlorite, also hornblendites	corroded magnetite grains indicate post-serpentinization
(Adjustments in consolidated bronzite-peridotite)	brecciated bronzite peridotite; antigorite and magnetite-clinochlore veins	hornblende occurs in the fragments, but not in the groundmass of the breccia: displacements along the veins have destroyed mesh texture
(Late serpentinization)	serpentinized hornblende	serpentine mineral appears to be antigoritic, therefore it was formed during regional metamorphism
6. Dolerite intrusion (hydrothermal activity and Ca metasomatism)	talc, anthophyllite and clinochlore; also rodingites	Dolerite intrusion was clearly post regional metamorphism
Late veining	chrysotile veins	persistent chrysotile probably post regional metamorphism

contact of the dolerite. Alternatively, the rodingites could have originated in the intervening ultrabasic material between the dolerite and the gneisses.

Garnet rodingite.—Specimen 39773 was found at 005108 in mixed float consisting of dolerite, pegmatite and weathered bronzite peridotite. No other rocks of this type have been found. The specimen is about 12" by 9" by 5"; at one end it is a uniform dark greenish rock of uneven hardness and from this it grades through a blotchy green, pink and white sugary rock to a dense, white, fine-grained "cherty" rock at the other end.

The dark greenish rock is composed of subround *garnets* in a chloritic groundmass. The garnet is in discrete colourless grains up to 3 mm in diameter, and in granular masses; it is weakly birefringent and makes up about 50% of the rock. Flakes of chlorite (pycnochlorite) (approx. 40%) 0.5 mm by 0.1 mm fill most of the interstices between the grains of garnet. Irregular grains of *diopside* (approx. 10%) are distributed throughout the chloritic groundmass. *Chromite* is present as rare euhedra or irregular translucent brown grains up to 0.1 mm in diameter.

The blotchy green, pink and white sugary rock is similar but contains only about 20% of chlorite, the pink colour being due to iron stains. The "cherty" rock is a fine-grained mass of nearly pure *garnet* (grossularite). This mass of garnet is traversed by yellow veins of diopside up to 1 mm wide. Also in the cherty rock are rare dark brown grains of allanite. Deep red iron staining is common in radiating cracks surrounding the allanite grains. The garnet adjacent to the allanite is noticeably more birefringent than that elsewhere.

Prehnite rodingite.—Specimen 39774 was collected from a stone heap at 005106. It is dense, white, "cherty", and of uniform hardness. *Prehnite* with its inclusions constitutes more than 90% of the rock and occurs in three ways: first as subhedral crystals, averaging 0.7 mm by 0.4 mm with curved fractures and abundant minute inclusions of high refractive index; second as clearer equant grains with coarse sutured contacts, which are up to 0.3 mm in diameter, and are arranged in more or less continuous strings; third as apparently formless masses with mottled interference colours. Examination of this material in suitable immersion oils revealed fine grains, averaging 0.05 mm in diameter which have sutured contacts with a material of much higher refractive index. This material has n 1.70 approx. and is probably *zoisite*. The remainder of the rock is made up of subhedral *diopside* prisms averaging about 0.4 mm in length.

Clinozoisite-diopside rodingite.—Several boulders of the clinozoisite-diopside rodingite where found at the contact of the ultrabasic racks with the country rocks at 015086. Specimen 39775 from this heap has a yellowish white groundmass enclosing sub-lenticular grey patches up to 3 mm in diameter. The groundmass consists of subhedral prisms of *diopside* up to 3 mm long, which are altered to clinozoisite and epidote around the margins. The grey patches are crystals of *clinozoisite*, which are up to 3 mm long, have simple twins on 001 and on 100 and are strongly zoned. Associated with the clinozoisite are veins composed of fine equant granules of epidote in a chloritic groundmass. The veins are about 1 mm wide and comprise 5% of the rock.

Diopside-prehnite rodingite.—Specimen 39776 was collected from the creek bed 100 feet west and 2,300 feet north of the south-west corner of the area. It is mottled grey with black spots and is traversed by numerous sub-parallel veins, up to 5 mm wide, of transversely oriented *actinolite*. Examination of the thin section with the naked eye and comparison with thin sections of bronzite peridotite shows a remarkable similarity in texture. Bronzite porphyroblasts have been replaced by clear *prehnite* grains with *zoisite* inclusions and the antigoritic groundmass has been replaced by murky *prehnite* with abundant fine inclusions and anhedral prisms of *diopside*. The diopside is commonly altered to amphibole or chlorite. Unfortunately, none of the original minerals of the bronzite peridotite remain. The texture however is unmistakeable. This particular rodingite is an altered bronzite peridotite.

Petrogenesis

The rodingite suite conforms to the chemical and mineralogical requirements of the rocks described by Marshall (1911, pp. 31-35), except in the presence of zoisite. The frequent occurrence of zoisite in rocks of this type was recognized by Grange (1927, p. 162).

In 1927 Grange reviewed the previous work on rodingites. and concluded that they were formed by the garnetization of gabbros. Grange considered that prehnite and grossularite were secondary after feldspar, but direct evidence that garnet formed after feldspar was not available; serpentinization of diallage was suggested as a source of lime and silica for these reactions.

Similar rocks have been described by various authors including Miles (1951) and Baker (1957).

The association of rodingites with ultrabasic rocks requires that ultrabasic rocks play an essential role in their formation. The present author considers that garnetization of gabbros is inadequate to explain the origin of the rodingites described here.

The rodingites from Nunyle show no relic gabbroic textures, but specimen 39776 has a texture derived from the bronzite peridotite, and specimen 39773 shows the association of garnet rodingite with a chloritic rock. These rocks are the result of alteration of ultrabasic rocks, and not of gabbros. Furthermore the serpentinization of calcic pyroxene cannot be invoked as a source of lime, since lime-rich minerals are not present in the bronzite peridotite.

The probable mode of formation of these rodingites therefore appears to be lime and alumina metasomatism of bronzite peridotites. Considering serpentine as the original mineral, the constituents of the rodingite suite could be derived as follows:—

1. $2H_2O.3MgO.2SiO_2$ (serpentine) + $3CaO$ + $4SiO_2$ = 3 $(CaO.MgO.2SiO_2)$ (diopside) + $2H_2O$.
2. $2H_2O.3MgO.2SiO_2$ (serpentine) + $3CaO$ + Al_2O_3 + SiO_2 = $3CaO.Al_2O_3 3SiO_2$ (grossularite) + $2H_2O$ + $3MgO$.
3. $2(2H_2O.3MgO.2SiO_2)$ (serpentine) + $6CaO$ + $5SiO_2$ + $3Al_2O_3$ = $3(2CaO.Al_2O_3.3SiO_2.H_2O)$ (prehnite) + H_2O + $6MgO$.
4. $4(CaO.MgO.2SiO_2)$ (diopside) + $3Al_2O_3$ + H_2O = $4CaO.3Al_2O_3.6SiO_2.H_2O$ (clinozoisite) + $2SiO_2$ + $4MgO$.

The reactions involve addition of lime, silica, alumina and water, and the removal of water, magnesia and silica. The removed oxides could be represented by the actinolite veins in specimen 39776.

The equations 1, 2 and 4 appear to be petrographically sound. Equation 3 is not supported by the petrography and prehnite is more probably derived by means of a two-stage reaction with either intermediate diopside or grossularite. The formation of prehnite by the decomposition of grossularite was recognized by Marshall (1911, p. 34), though it is probable that the prehnite, which is pseudomorphous after bronzite, was formed in some other manner.

The source of the metasomatic fluids was certainly neither the ultrabasic rocks nor the pegmatites but probably the quartz dolerite dykes which contain abundant alumina and lime. However, there are two difficulties connected with such a source; first, hydrothermal action clearly connected with the dolerite has given rise to talc and anthophyllite; second, the later stages of dolerite intrusion were sodic rather than calcic. Nevertheless, the present author considers that this rodingite suite is the product of fluids derived from the dolerite dyke acting on the bronzite peridotite.

The Country Rocks

Introduction

The country rocks in the area studied consist of gneisses, quartzites and basic granulites. There are not granite batholiths in the immediate vicinity, though in places the gneisses are intruded by narrow dioritic dykes, which are a few feet wide.

Gneisses make up most of the rocks in the district and vary from almost massive to strongly foliated and lineated. Half a mile to the east and west of the ultrabasic body the trends in the gneisses are remarkably uniform and the dip is steep to the east. To the south of the area the trends are disturbed by an east-west trending fault or shear zone along which the northern block appears to have moved east. Outcrops of gneiss are fair on the hill slopes and excellent in the creek beds.

The quartzites occupy a north-south strip of country which varies from 300 feet wide to 600 feet depending on the dip and other structural features. They are generally coarse-grained and in the north-west corner of the area, euhedral quartz crystals, up to 6" in length, are common. Foliation and lineation are well-developed in the quartzite except where they are obscured by the very coarse grain-size. No cross-bedding, ripple marks or other primary sedimentary structures have been observed in the area. The quartzite probably had rather impure bands which gave rise to garnetiferous quartzite; this rock has only been seen on talus slopes and its stratigraphic location within the quartzite is unknown. Lenses or bands of basic granulites occur within the quartzite. Benches and belts of red soil traversing the quartzite indicate that these are common, but proof in the form of solid outcrops is seldom available. Outcrops of quartzite are good, constituting the highest features in the area.

The basic granulites appear as lenses and boudins in the gneiss and quartzite, and are generally of the order of 10 to 20 feet wide. Outcrops are only fair except in the creek beds, where boudin structures are well-developed and original beds may be traced as strings of discrete boudins. It is probable that the basic granulites occur everywhere as boudins and lenses, and no continuous bands remain, but the general paucity of outcrop of this rock type makes this uncertain. Foliation is not well-developed but lineation is evident on close examination in hand specimen. The basic granulites have been studied in detail as they are the best metamorphic facies indicators in the area.

Metamorphic Facies

Recognition of the grade of metamorphism is generally dependant on the presence of a diagnostic mineral assemblage and at Nunyle such assemblages are rare, so that no conclusion has been reached regarding the exact metamorphic grade of the country rocks at the time the bronzite peridotite was intruded. In the absence of diagnostic assemblages, a study of all the assemblages in the country rocks has indicated a definite trend in the metamorphism of the area.

Seven mineral assemblages occur in the country rocks:

1. Hypersthene-andesine-hornblende.
2. Diopside-andesine-hornblende.
3. Microcline-oligoclase-biotite-quartz.
4. Quartz-muscovite.
5. Oligoclase-hornblende-biotite.
6. Chlorite-muscovite-epidote-actinolite.
7. Saussurite-hornblende-quartz.

Of these, the first four evidently represent the metamorphic facies prior to the intrusion of the bronzite peridotite. Granoblastic textures, with little or no sign of corrosion occur in rocks containing these assemblages. Assemblages 3 and 4 have no diagnostic value, but 1 and 2 indicate high amphibolite or granulite facies. Abundant greenish yellow hornblende may be due to F^- or $(OH)^-$ in the rock inhibiting the development of more than one type of pyroxene and so masking the exact facies assemblage.

Assemblage 5 has resulted from down-grading of 1 and 2. The hornblende is green containing small blebs of quartz and is characteristically coarser in grain-size than the greenish yellow hornblende in assemblages 1 and 2.

Assemblage 6 is of the lowest metamorphic grade and occurs only in a shear zone, which passes through 118063. The temperature had fallen before the shearing, so that the rocks within the zone have recorded the intensified retrogressive metamorphism.

Assemblage 7 has resulted from saussuritization adjacent to the dolerite dyke at 012233. A similar assemblage of hornblende-saussurite-chlorite is partly developed at 194063.

The highest metamorphic grade was attained some time before the intrusion of the bronzite peridotite, when all the basic rocks contained pyroxene. The temperature fell prior to the bronzite peridotite intrusion so that at the time of the intrusion, where there was differential movement and possibly the introduction of OH^-, pyroxene-andesine-hornblende recrystallized to oligoclase-hornblende (which may represent low amphibolite facies). Shearing took place at still lower temperatures producing low grade rocks in restricted loci. Minor subsequent alteration has been caused throughout all the country rocks by fluids which accompanied the dolerite intrusion.

Petrogenesis

All of these rocks have been completely recrystallized, and, with the exception of bedding, no primary structures are preserved. The bulk composition has probably not altered greatly, except in the addition of alkalies to the gneiss.

The gneisses and quartzite are lineated, bedded and appear to be conformable.

The origin of the basic granulites has been clearly demonstrated by Prider (1944, p. 121), who described and analysed rocks similar to those at Nunyle. Originally these were tholeiitic flows or sills which recrystallized to form pyroxene-andesine-hornblende granulites, some of which were later altered to oligoclase-hornblende granulites. During this alteration there was no significant change in the bulk composition.

At Nunyle the alteration to oligoclase-hornblende granulites has only occurred in critical localities where there have been structural adjustments with attendant rock flowage.

Summary and Economic Considerations

The rocks at Nunyle consist of gneisses, quartzites and interbedded pyroxene-andesine-hornblende granulites, similar to those of the Jimperding "Series" described elsewhere. They have been developed by metamorphism accompanied by regional folding, of the original sandstones, sandy claystones and tholeiitic sills or flows.

After the main period of folding the bronzite peridotite was injected. During the intrusion, gneiss and basic granulites were mobilized in certain critical localities, with the result that some of the pyroxene-andesine-hornblende granulites were converted to oligoclase-hornblende granulites. At the same time there was further folding of the quartzite.

Intrusion of pegmatite dykes followed the consolidation of the bronzite peridotite. Emanations from these produced talc, anthophyllite and clinochlore in the ultrabasic mass.

The rocks were subsequently intruded by dolerite dykes, which caused epidotization in the country rocks and minor hydrothermal alteration in the ultrabasic mass, and were probably also responsible for the formation of the rodingites.

The high Mg/Fe ratio and lack of associated gabbro place the Nunyle bronzite peridotite in the class of alpine type serpentinites. Alpine type serpentinites rarely carry metallic mineralization but may be favourable loci for chrysotile asbestos deposits. As only moderate thermal metamorphism will cause alteration of chrysotile to antigorite Archaean deposits are not likely to have survived. It would be interesting to know if the late chrysotile veins have formed as a result of continued serpentinization of high temperature silicates or by solution of antigorite and redeposition of chrysotile.

In the past by far the greatest production of chrysotile has come from rocks of post-Archaean age but there are significant producing mines situated within the shield areas. The ultrabasic mass at Nunyle is small and contains a very low percentage of chrysotile. Other serpentinites of similar age will certainly be found in the district as geological mapping proceeds and it is possible that one of these may prove to be of economic interest.

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References

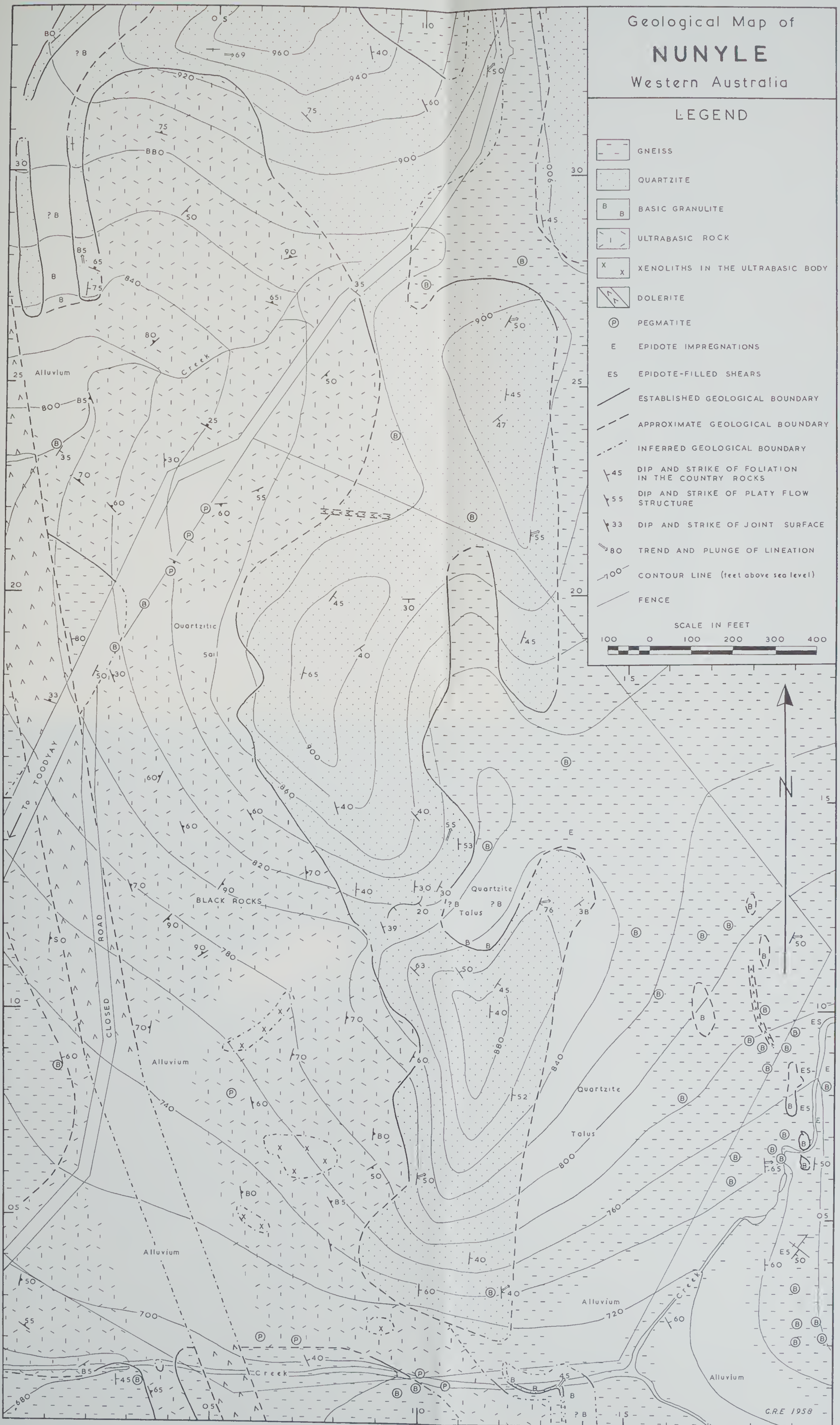
Baker, G. (1957). Nickeliferous serpentinite and rodingite from Anderson's Creek Area, near Beaconsfield, Northern Tasmania. C.S.I.R.O. (Mineragraphic Investigations) Rep. No. 682.

Barshad, I. (1948).—Vermiculite and its relation to biotite as revealed by base exchange reactions, X-ray analyses, differential thermal curves and water content. *Amer. Min.* **33**: 655-678.

Bowen, N. L. and Tuttle, O. F. (1949).—The system $MgO - SiO_2 - H_2O$. *Bull. Geol. Soc. Amer.* **60**: 439-460.

Clarke, E. de C. (1930).—The Pre-Cambrian succession in some parts of Western Australia. *Rep. Aust. Ass. Advance. Sci.* **20**: 155-192.

Dana, E. S. (1954).—"A Textbook of Mineralogy." 4th Ed. (Wiley: New York.)


Geological Map of
NUNYLE
Western Australia
LEGEND
GNEISS
QUARTZITE
BASIC GRANULITE
ULTRABASIC ROCK
XENOLITHS IN THE ULTRABASIC BODY
DOLERITE
PEGMATITE
EPIDOTE IMPREGNATIONS
EPIDOTE-FILLED SHEARS
ESTABLISHED GEOLOGICAL BOUNDARY
APPROXIMATE GEOLOGICAL BOUNDARY
INFERRED GEOLOGICAL BOUNDARY
DIP AND STRIKE OF FOLIATION IN THE COUNTRY ROCKS
DIP AND STRIKE OF PLATY FLOW STRUCTURE
DIP AND STRIKE OF JOINT SURFACE
TREND AND PLUNGE OF LINEATION
CONTOUR LINE (feet above sea level)
FENCE
SCALE IN FEET
100 0 100 200 300 400
N
Alluvium
Creek
Quartzitic Soil
BLACK ROCKS
To TOODYAY
ROAD CLOSED
Quartzite
Talus
G.R.E 1958